Energy efficiency and carbon footprint reduction for Croatian regions by Total Site integration

Stanislav Boldyryev, Goran Krajačić
Department of Energy, Power Engineering and Environment, Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Ivana Lucica 5, HR-10002 Zagreb, Croatia
stas.boldyryev@fsb.hr

ABSTRACT

EC presented new energy targets that have to be achieved until 2030, the energy efficiency should be increased on 27%. Energy saving has an important role in achieving a sustainable future development. It can be done by heat recovery at Site level that provides a considerable potential for energy saving. The use of excess heat gives a way to reduce the use of primary energy and to contribute a global CO_2 mitigation. The methodology can be successfully implemented in different regional sites including industrial, commercial, residential, utility etc.

This paper is focused on allowing heat recovery for district heating needs of both new designs and as retrofits to existing sites to ensure fast, widespread and cost-efficient industrial deployment. The main objective of this work is the carbon footprint reduction and energy efficiency via development an advanced techniques for Total Site integration and it will be developed by CARBEN project.

KEY WORDS

Total Site Analysis, Heat Integration, Energy Efficiency, Industrial Application.

INTRODUCTION

Since EU leaders agreed on the 2030 climate and energy policy framework the energy efficiency is becoming high priority for the next 15 years. On 23 October, EU leaders agreed on the 2030 climate and energy policy framework for the EU [1]. The European Council today endorsed four targets:

- a binding EU target of at least 40% less greenhouse gas emissions by 2030, compared to 1990;
- a binding target of at least 27% of renewable energy used at EU level;
- an energy efficiency increase of at least 27%;
- the completion of the internal energy market by reaching an electricity interconnection target of 15% between members states and pushing forward important infrastructure projects.

The energy efficiency improvement is one of the key goals for future sustainable development. As reported by [2] the industrial energy consumption in 2012 was 28% of overall world energy balance (see Fig. 1). Energy saving potential in industry is still huge despite the last time there are a lot of researches and applications that allowed reducing energy consumption considerably. Most of them are based on pinch analysis, mathematical programming and life cycle assessment as well as combinations and modifications of these methods as reported in [3]. For example, Čuček L. et al, in [4] proposed the multi-period synthesis of an optimally integrated regional biomass and bioenergy supply network through a mixed-integer linear programing (MILP) approach. They obtained solutions with optimal selection of raw materials, technologies, intermediate and final product flows, and reduced greenhouse-gas emissions. In [5] presented combination of mathematical programming and life cycle assessment for biomass and bioenergy supply chain. In work [6] delivered the application of pinch analysis for chemical plant and shown the reduction of energy consumption on 45%.

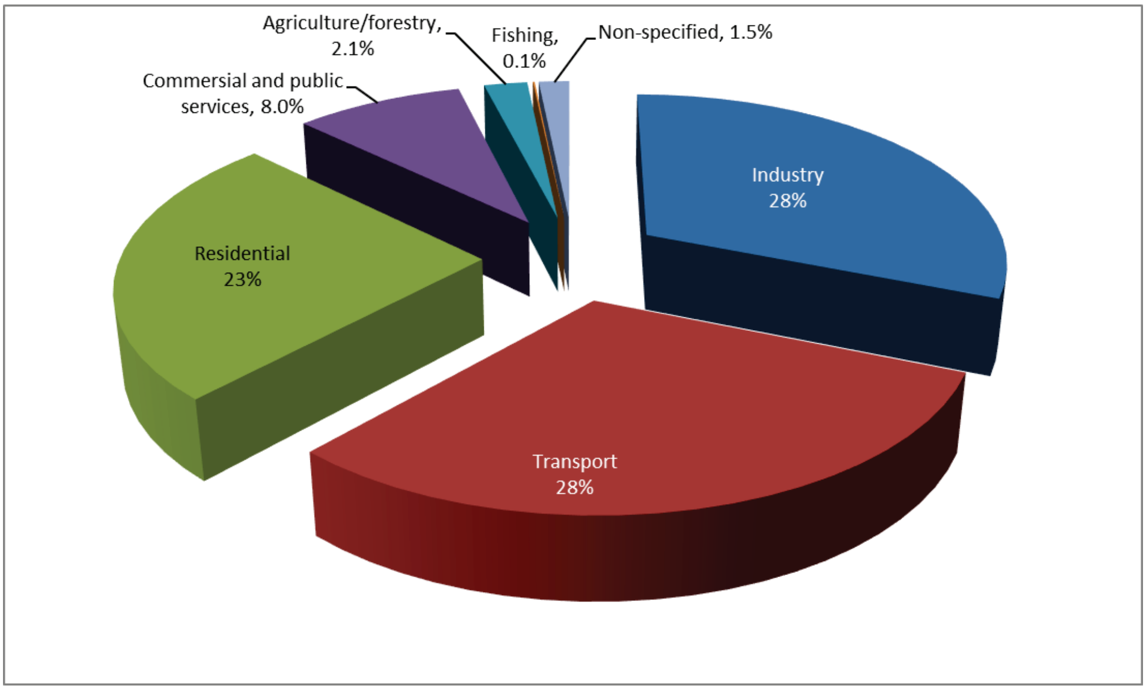

Figure 1. World energy balance 2012 (source IEA).

Last time big progress in energy efficiency improvement of individual industrial process was reached and more attention should be paid to industrial sites. Firstly, it allows reducing energy consumption of industrial regions and decreasing pollution reduction considerably, secondly, it provides the possibility to utilise the industrial heat for residential and commercial sectors that are still big energy consumers. From the other hand, it makes appropriate background to implement alternative energy sources including renewables that leads additional reduction of energy costs and improves environmental impact. These measures needs well developed approaches that solve this type of system objectives. To utilise the waste industrial heat for different needs on site level the Total Site Analysis (TSA) should be used as was reported in [7]. More recent developments shown that it could be based on different approaches. Karimkashi S. and Amidpour M. [8] proposed a method for analysis an industrial energy system. It is based on the development and modifications of the R-curve concept, which was previously developed by Kimura H. and Zhu X.X. [9] and later updated by Varbanov R. et al [10]. It was also used in [11] to estimate the investments of Total Site power cogeneration.

Hackl R. et al in [12] analysed large chemical site with use of the total site analysis (TSA) method and proposed retrofit shown 50% energy saving. However, for low potential industrial heat utilisation the Total Site heat recovery can be used. Authors in [13] proposed the intermediate utility use. This method was later updated in [14] and provided a methodology for minimisation of heat transfer area of Total Site heat recovery systems. Last time the authors were concentrated on development of methodology which allow minimise the heat transfer area of heat recovery on Total Site level. Using intermediate utilities for heat recovery system was developed and explained in details. Therefore, it was the significant step in estimation of retrofit targets of industrial site.

In this paper proposed the methodology to estimate minimum cost for retrofit of Total Site heat recovery systems including energy and investments.

METHODOLOGY

The authors previously proposed the procedure for estimating heat transfer area, which depends on a certain temperature levels of intermediate utility as reported in [14]. It dealt with minimum heat transfer area for Total Site heat recovery. But there are other constituents of investments during retrofit such as numbers of heat exchangers as reported by Ahmad S. et al [15], specific temperature difference, utility targets, utility levels and prices which are influenced on total cost as shown by Kemp I.C. [16]. Methodology grounded on basic principles of pinch-analysis [17] with some features of Total Site heat recovery. Last time a lot of researches on Total Site heat recovery investigate the possible heat integration without changing of temperature approach between Site profiles and do not take into account the costs for retrofit [18].

Total cost targeting

The procedure of total costs estimation for Total Site heat recovery is consisted from the following steps:

- Putting Total Site profile specifying minimum possible ΔT_{min} between profiles
- Determination of enthalpy intervals
- Selection optimum level of intermediate utilities
- Calculation of numbers of heat exchangers (boilers and condensers, heaters and coolers)
- Calculation of energy consumption
- Calculation of total costs
- Changing the ΔT_{min} between profiles and repetition of previous steps

Alternatives between big and small values of Total Site recovery are illustrated on Fig. 2.

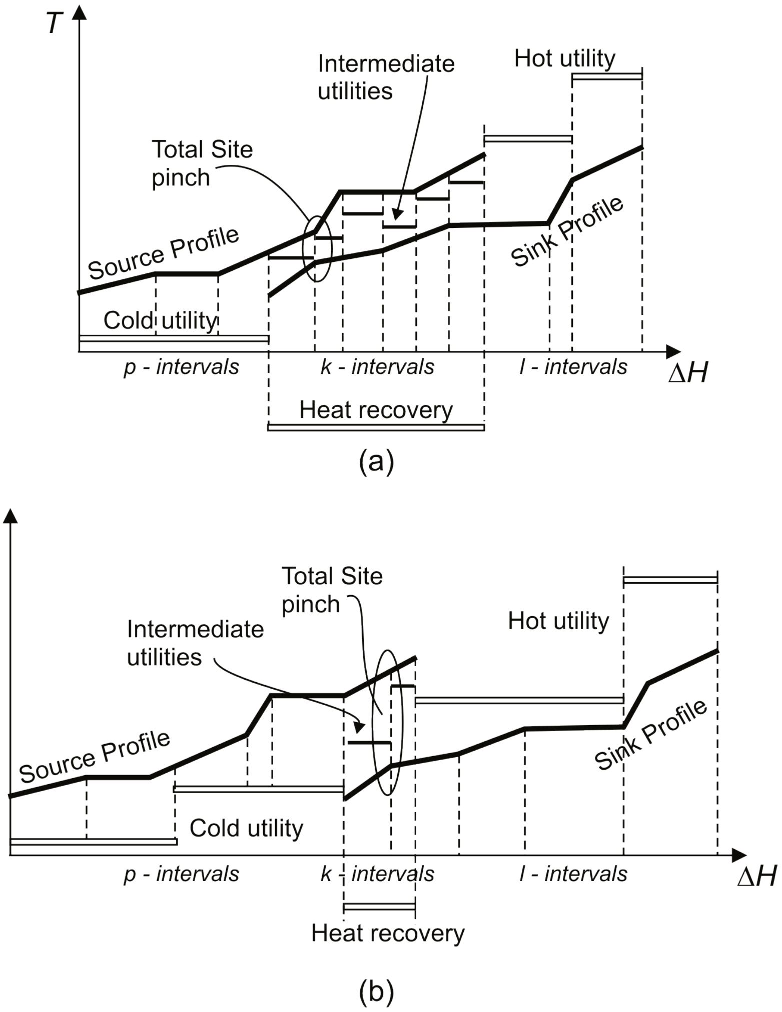

Figure 2. Total Site profiles: a – expensive energy, big recovery; b – cheap energy, small recovery (developed after [19]).

Heat transfer area and number of heat exchangers

The heat transfer area is calculated for heat recovery regions, hot and cold utility regions (Eq. 1):

$$A_{Total} = A_{TSHR} + A_{TSHU} + A_{TSCU} A_{Total} = A_{TSHR} + A_{TSHU} + A_{TSCU} \qquad (1)$$

The heat transfer area for hot and cold utility regions is calculated as reported in [17] but for different levels of utility selecting the level of utility with minimal heat transfer area (Eq. 2 and 3).

$$A_{TSHU} = \sum_{i=1}^{l} \min_{t1<t_{HU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{HU}}{h_{HU}} \right)_i \qquad (2)$$

$$A_{TSCU} = \sum_{j=1}^{p} \min_{t1<t_{CU}<t2} \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{CU}}{h_{CU}} \right)_j \qquad (3)$$

For calculation of minimum heat transfer area on heat recovery, the (Eq. 4) modified in [14] is used:

$$A_{TSHR} = \sum_{z=1}^{k} \min_{t1<t_{IM}<t2} \left(\frac{1}{\Delta T_{LM}^{H}} \left(\sum_{i=1}^{n} \frac{Q_i}{h_i} + \frac{Q_{IM}}{h_{IM}^{H}} \right) + \frac{1}{\Delta T_{LM}^{C}} \left(\sum_{j=1}^{m} \frac{Q_j}{h_j} + \frac{Q_{IM}}{h_{IM}^{C}} \right) \right)_z \tag{4}$$

The numbers of utility heat exchangers are calculated from basic principles of pinch-analysis [17] assuming the number of heat exchangers are equal the number of streams in each enthalpy interval and minimisation of heat transfer area.

$$N_{HU} = \sum_{i=1}^{l} n_i^c, \qquad N_{CU} = \sum_{i=1}^{p} n_i^h \tag{5}$$

The number of heat exchangers for heat recovery is calculated for Sink and Source side. There are the dimensions of heat boilers and condensers for steam-condensate intermediate utility and heaters and coolers for hot water intermediate utility (Eq. 6). It different from calculation of process-to-process heat exchangers because of different intermediate utility for enthalpy interval of heat recovery.

$$N_{HR} = \sum_{i=1}^{k} n_i^h + n_i^c \tag{6}$$

Total numbers of heat transfer equipment for Total Site heat recovery are calculated from the Eq. 7:

$$N_{Total} = N_{HR} + N_{HU} + N_{CU} \tag{7}$$

The Fig. 3 well illustrates the numbers of heat exchangers and definition of heat transfer area in enthalpy interval of Total Site profiles.

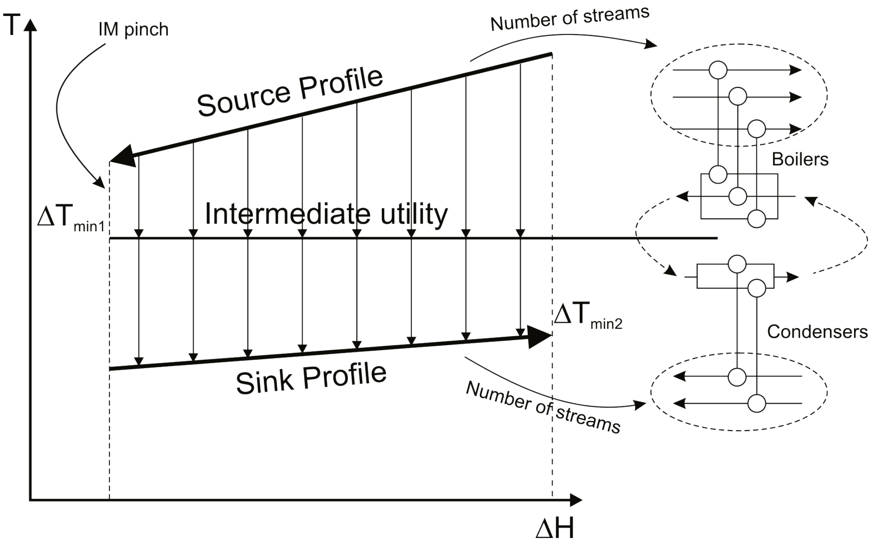

Fig. 3. Streams and heat exchangers in enthalpy interval with intermediate utility (developed after [16]).

The energy consumption

For the last step, the determination of utility demands, fuel and cooling media consumption is needed. Hot and cold utilities demand for each Site ΔT_{min} are defined from Total Site profiles [7] and it is shown on Fig. 2. Total Site fuel consumption can be calculated from hot utility demands, ambient temperature, temperature of flue gases, coefficient of excess air and furnace efficiency. Cold utility consumption (e.g. cooling water, hot water, refrigerants etc.) can be determined from cold utility demands, temperature differences and efficiency.

The investment costs of Total Site heat recovery are calculated from minimum heat transfer area (Eq. 1), numbers of heat transfer equipment (Eq. 7) and prices of equipment. The energy costs are defined from Total Site energy targets as said above and energy prices depending on utility types.

CASE STUDY

There are three processes included in this case study considered in the Total Site Analysis and all process streams are accounted for when constructing Total Site Profiles, described in [13]. During pinch analysis of two individual production factories (Processes A and B), the huge amount of heat was recovered. However, these processes still need external heating and cooling as presented on Fig. 4. Besides the there are some consumers of heat at areas around these factories. Process C consist of power substation, school, commercial and residential areas. Utility demands and surplus of the site created by Processes A, B and C were analysed by Total Site methodology with use of intermediate utilities. Total Site Profiles were built with use of Grand Composite Curves of Processes A and B and streams of Process C from Table 1.

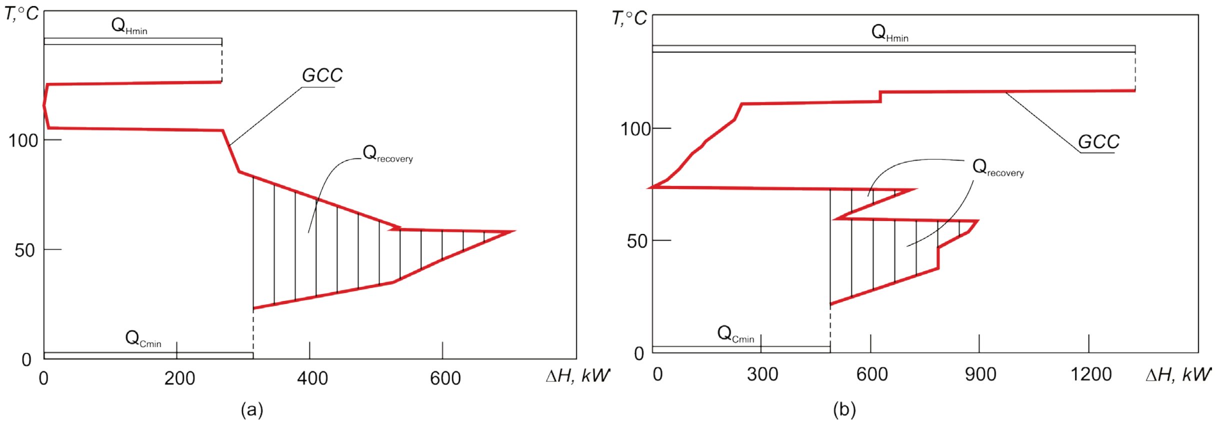

Figure 4. Grand composite curves (GCC) of existing production processes.
(a) – Process A, Q_{Hmin}=267 kW; Q_{Cmin}=320 kW, $Q_{recovery}$=684 kW;
(b) – Process B, Q_{Hmin}=1328 kW; Q_{Cmin}=485 kW, $Q_{recovery}$=817 kW.

Table 1. Stream data of Process C

Stream	Type	TS (°C)	TT (°C)	CP (kW/°C)	ΔH (kW)	*h* (kW/(m^2 C))
District heating	cold	50	90	3.490	139.6	1.0
Hot water supply of residential area	cold	20	50	16.296	488.9	1.0
Hot water supply of commercial area	cold	20	50	6.984	209.5	1.0

The Source Profile requires 800 kW of the external cooling capacity and hot utility target is 2433 kW of low-pressure steam. The prices of utilities are 350 USD/kWy and 35 USD/kWy for hot and cold utility respectively.

In order to perform heat recovery an intermediate utility is needed (see Fig. 5). The overlapping part representing the heat recovery was distributed by enthalpy intervals. There are two kinks on the Sink Profile on heat recovery of this case study. These breakpoints create 2 enthalpy intervals as presented in Fig. 5 and 2 intermediate utilities are used. The temperatures of the intermediate utilities are limited by the Sink and Source Profile temperatures. The temperature range of first intermediate utility is from 36 ºC to 53 ºC, for second intermediate utility is from 53 ºC to 64 ºC. The minimum temperature difference of the Total Site heat recovery systems is 5 ºC that may be achieved by use of plate heat exchangers. The Total Site analysis shows the possibility for energy efficiency improvement by use of intermediate utility. In this case study, the heat recovery is increased on 744 kW, wherein hot utility (low pressure steam) is reduced from 2433 kW to 1689 kW and cold utility (cooling ware) reduction is 93% from 800 kW to 56 kW.

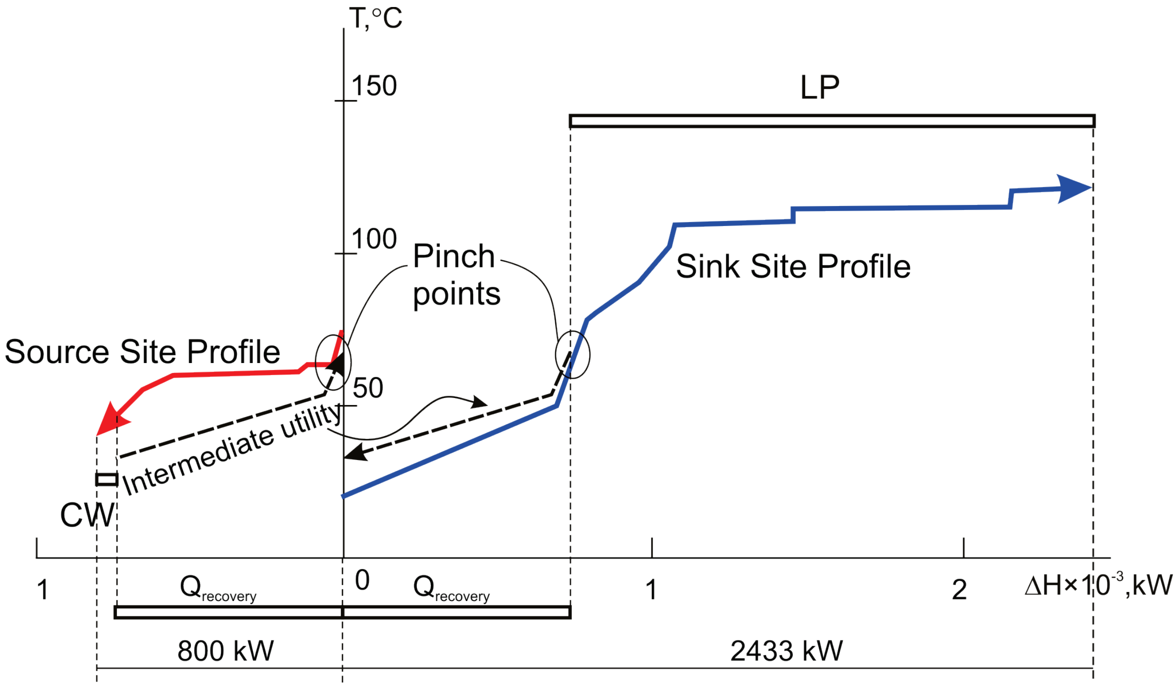

Figure 5. Total Site Profiles. LP=1689 kW; CW=56 kW; $Q_{recovery}$=744 kW.

The realization of retrofit project of site heat recovery requires additionally 272 m^2 of heat transfer area and 8 heat exchangers. The estimated capital cost of this retrofit project is 297,600 Euro. These investments lead to annual economy of 182,490 Euro by Total Site heat recovery and provide utilisation of low potential industrial heat for site wide demands. The simple payback period of site heat recovery system is 19.6 month. The results of case study are collected in Table 2.

Table 2. Results of Total Site integration

	Hot utility (kW)	Cold utility (kW)	Recovery (kW)	Investment (EUR)	Saving (EUR)	Payback time (months)
Existing process	2,433	800	0	–	–	–
Retrofit	1,689	56	744	297,600	182,490	19,6

DISCUSSION

The paper is a step ahead to application the Total Heat Site heat recovery methodology to real cases and providing the decision making tool for the managers during retrofit and new projects. However, there are some things are still needed deeper discussion and investigation.

The heat exchangers network for Total Site heat recovery is consisted of multiple steam boilers, condensers, water heaters and coolers. This equipment proposed to be placed for each enthalpy interval but it is still the possibility to simplification of heat exchangers network and finding the most profitable way between numbers of units and heat transfer area.

The number of heat exchangers heat transfer area is increased comparison to individual process heat recovery due to heat transfer via intermediate utility. From the other hand heat transfer coefficient for phase change is much higher than for heating and cooling of liquids and gases. In this case, the heat transfer area has to be minimized as mentioned above and combined with numbers of units.

Calculating the total cost of heat recovery integration on Total Site the trade-off is determined. Energy costs have a big influence on this and using of different energy sources will should be researched here. Low price energy sources move the retrofit project for low heat recovery to bigger energy consumption. It will decrease even realization of retrofit project which is so important for industrial site operation mode. This retrofit can be done during short time scheduled maintenance. To reduce this energy prices the renewables can be integrated into the Total Site but this should be well analysed from scheduling point of view and appropriate placement into the Site.

The additional analysis of Total Site heat recovery systems should be delivered in future work with attention to capital cost reduction by use the methodology of selection of optimal level of intermediate utility and possibility for cogeneration of heat and power. The design of Total Site heat exchangers network deserves further attention as well as revamp. The summer operation mode should be analysed additionally. During this period, the heating and cooling demands will be changed and operation of heat exchangers network has to be updated as well.

CONCLUSION

The method allows to estimating minimum total cost for retrofit of Site heat recovery systems. It let makes a recommendation for selection of numbers of heat exchangers, numbers and levels of intermediate utility, hot and cold utility consumption on Total Site level.

The Total Site analysis was accomplished and the possibility of low potential waste heat utilisation was determined. The heat recovery on Total Site level is increased on 744 kW by use of intermediate utility. These changes reduce site heating demands on 31% and cooling demands on 93%, the estimated capital costs of retrofit project requires 297,600 Euro and payback time is 19.6 months. The use of excess heat can provide a way to reduce the use of primary energy and to contribute to global CO_2 mitigation.

The results of this work may be used for further developments in Total Site methodology for capital cost assessment with use of gas and steam turbines, renewables and specific process operations.

ACKNOWLEDGMENT

The financial support by the EC and Croatian Ministry of Science Education and Sports project "CARBEN" (NEWFELPRO Grant Agreement No. 39).

NOMENCLATURE

T – temperature, °C;
ΔH – enthalpy, kW;
A_{total} – total heat transfer area, m^2;
A_{TSHR} – minimum heat transfer area of heat recovery, m^2;
A_{TSHU} – minimum heat transfer area of hot utility, m^2;
A_{TSCU} – minimum heat transfer area of cold utility, m^2;
ΔT_{min} – minimal temperature difference between two process streams, °C
ΔT_{min1} – minimal temperature difference for source side, °C
ΔT_{min2} – minimal temperature difference for sink side, °C
ΔT_{LM}^{H} – logarithmic temperature difference for source side, °C
Error! Objects cannot be created from editing field codes. – logarithmic temperature difference for sink side, °C
Q_i – heat of i hot stream, kW;
Q_j – heat of j cold stream, kW;
Q_{IM} – heat of intermediate utility in enthalpy interval, kW;
$Q_{RECOVERY}$ – load of heat recovery, kW
Q_{HU} – heat of hot utility in enthalpy interval, kW;
Q_{CU} – heat of cold utility in enthalpy interval, kW;
Q_{Hmin} – hot utility target, kW;
Q_{Cmin} – cold utility target, kW;
h_i – film heat transfer coefficient of i process stream, W/(m^2 °C);
h_j – film heat transfer coefficient of j process stream, W/(m^2 °C);
h_{IM}^{C} – film heat transfer coefficient for condensation of intermediate utility, W/(m^2 °C);
h_{IM}^{H} – film heat transfer coefficient for boiling of intermediate utility, W/(m^2 °C);
h_{HU} – film heat transfer coefficient of hot utility, W/(m^2 °C);
h_{CU} – film heat transfer coefficient of cold utility, W/(m^2 °C);
n – number of hot streams in enthalpy interval;
m – number of cold streams in enthalpy interval;
k – number of enthalpy intervals for heat recovery;
l – number of enthalpy intervals for hot utility;
p – number of enthalpy intervals for cold utility;
N_{HU} – number of heat exchangers for hot utility;
N_{CU} – number of heat exchangers for cold utility;
N_{HR} – number of heat exchangers for heat recovery;
N_{Total} – total number of heat exchangers;
CW – cooling water, kW;
LP – low pressure steam, kW;
n_i^h – number hot streams in enthalpy interval;
n_i^c – number hot streams in enthalpy interval.

REFERENCES

1. European Commission Climate Action <http://ec.europa.eu/clima/policies/2030/index_en.htm> accessed 04.02.2015
2. IEA (International Energy Agency) <http://www.iea.org> accessed 26.01.2015
3. Klemeš J. J., Varbanov P. S., Liew P. Y., Čuček L., Kravanja Z., Wan Alwi S. R., Abdul Manan Z., Recent developments in advanced process integration: Learning the lessons from industrial implementations, *Applied Mechanics and Materials*, Vol. 625, pp 454-457, 2014.
4. Čuček L., Martín M., Grossmann I. E., Kravanja Z., Multi-period synthesis of optimally integrated biomass and bioenergy supply network, *Computers & Chemical Engineering*, Vol. 66, pp 57–70, 2014.
5. Čuček, L., Klemeš, J.J., Varbanov, P.S., Kravanja, Z., Life cycle assessment and multi-criteria optimization of regional biomass and bioenergy supply chains, *Chemical Engineering Transactions*, 25, 575-580, 2011.
6. Boldyryev, S., Varbanov, P.S., Process integration for bromine plant, *Chemical Engineering Transactions*, Vol. 39, 1423-1428, 2014.
7. Klemeš J.J., Dhole VR, Raissi K, Perry S, Puigjaner L., Targeting and design methodology for reduction of fuel, power and CO_2 on total sites, *Applied Thermal Engineering*, Vol. 17, No. 8–10, pp 993–1003, 1997.
8. Karimkashi S., Amidpour M., Total site energy improvement using R-curve concept, *Energy*, Vol. 40, No 1, pp 329–340, 2012.
9. Kimura H., Zhu X.X., R-Curve concept and its application for industrial energy management, *Ind Eng Chem Res*, Vol. 39, 2315–2335, 2000.
10. Varbanov P., Perry S., Makwana Y., Zhu X.X., Smith R., Top-level Analysis of Site Utility Systems, *Chemical Engineering Research and Design*, Vol. 82, No. 6, pp 784-795, 2004.
11. Boldyryev, S., Varbanov, P.S., Nemet, A., Klemeš, J.J., Kapustenko, P., Capital Cost Assessment for Total Site Power Cogeneration, *Computer Aided Chemical Engineering*, Vol. 32, pp 361-366, 2013.
12. Hackl R., Andersson E., Harvey S., Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA), *Energy*, Vol. 36, no 8, 4609–4615, 2011.
13. Nemet, A., Boldyryev, S., Varbanov, P.S., Kapustenko, P., Klemeš, J.J., Capital cost targeting of total site heat recovery, *Chemical Engineering Transactions*, Vol. 29, pp. 1447-1452, 2012.
14. Boldyryev, S., Varbanov, P.S., Nemet, A., Klemeš, J.J., Kapustenko, P., Minimum heat transfer area for Total Site heat recovery, *Energy Conversion and Management*, Vol. 87, pp 1093-1097, 2014.
15. Ahmad S, Linnhoff B, Smith R., Cost optimum heat exchanger networks – 2. Targets and design for detailed capital cost models. *Comput Chem Eng*, Vol. 14, No 7, pp 751–767, 1990.
16. Kemp, I.C. *Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient use of Energy*. Elsevier, Amsterdam, The Netherlands, 2007.
17. Smith R., *Chemical Process Design and Integration*, McGraw-Hill, New York, USA, 2005.
18. Chew K.H., Klemeš J.J., Wan Alwi S. R., Abdul Manan Z., *Applied Thermal Engineering*, Vol. 78, pp 731-739, 2015.
19. Dhole V.R., Linnhoff B., Total site targets for fuel, co-generation, emissions, and cooling. *Comput Chem Eng*, Vol. 17, 101–109, 1993.